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Distributed and Self-Adaptive Microfluidic Cell Cooling for CPV Dense Array Receivers

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Abstract. Temperature non uniformities of the CPV receivers lead to mismatch losses. In order to deal with this issue, a cooling device, formed by a matrix of microfluidic cells with individually variable coolant flow rate, has been developed. This device tailors the distribution of the heat extraction capacity over the CPV receiver to the local cooling needs in order to reduce the temperature non uniformities with respect to microchannel devices when submitted to uniform or non-uniform illumination profiles. At equal average temperature of the CPV receiver, power generation applying the matrix of microfluidic cells with individually variable coolant flow rate is 9.7% higher than the one with conventional microchannel technology.

INTRODUCTION

Concentrating photovoltaics (CPV) is a promising technology to reduce the cost of the PV power generation. The cooling of dense array CPV receivers must reach low thermal resistance coefficients below 10^{-4} m^2K/W [1], high compactness and relevant capacities to provide a high temperature uniformity of the PV receiver, both for reliability and efficiency issues [2,3]. Several works have assessed the impact of cooling schemes on the performance of the CPV devices when submitted to constant heat loads [4,5]. They showed than the optimum flow rate varies with the solar concentration. Some works [6] have shown the capacity of improved microchannel cooling schemes to obtain, through an adequate design, uniform temperature profiles when submitted to uniform and non-uniform heat flux distributions. Nevertheless, the heat flux distribution on a CPV receiver is non-uniform and time dependent [7]. As a consequence, cooling devices with constant and uniform flow rate distributions are overly conservatives and lead to non-uniform temperature distributions and oversized pumping powers. Temperature non uniformities increase the mismatch losses and mechanical stresses throughout the receiver, which causes reliability losses [8]. Furthermore, the pumping power needed to decrease the PV cells temperature and, therefore, to increase the PV efficiency, must be balanced with the PV output in order to find the optimum working point [7].

In this work, the impact of a cooling device, formed by a matrix of microfluidic cells with individually variable coolant flow rate, on the performance of a CPV receiver is assessed under non-uniform and time dependent heat load scenarios and compared to conventional microchannels.

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DESCRIPTION OF THE COOLING DEVICE

In the proposed configuration, the coolant (water) is distributed towards a matrix of microfluidic cells (Figure 1(a)). Each microfluidic cell has a temperature controlled microvalve [9] that self-adapts the cell flow rate to the local temperature. The microvalves adapt the coolant flow rate in each cell to the minimum required to maintain a desired temperature, allowing higher flow rates when the temperature rises due to increased local heat load. By adapting to the local heat extraction needs, the temperature is made more uniform across the cell array. The studied internal geometry of the microfluidic cell uses tailored fins (Figure 1(b)) to improve the temperature uniformity within a single cell and the flow path is short in order to reduce the pressure losses. The self-adaptive thermostatic microvalves (Figure 2) are located near the coolant outlet and on the hot side of each microfluidic cell and provides a coolant flow rate that increases significantly when the cell reaches a design operating temperature. The valve operates on a thermostatic principle, where the thermal expansion of the valve body with respect to the substrate will open an orifice allowing an increase in coolant flow rate. This self-adaptive microvalve principle has been previously modeled and experimentally demonstrated for a single cell [9], but is applied in this study to a matrix of solar cells. This novel approach aims to increase the reliability of the CPV receiver by minimizing the thermal cycling (time variations) and thermomechanical stresses (spatial variations), as well as minimize the time dependent pumping power.

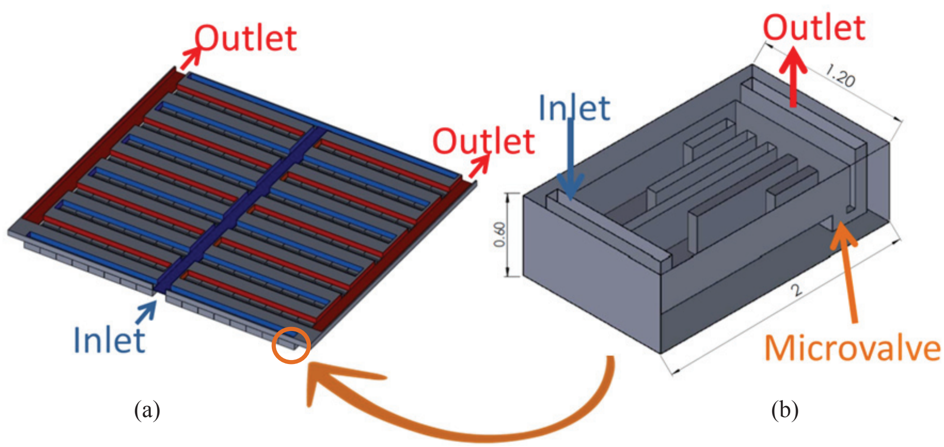

FIGURE 1. (a) Coolant distribution on the cell matrix (b) Microfluidic cell

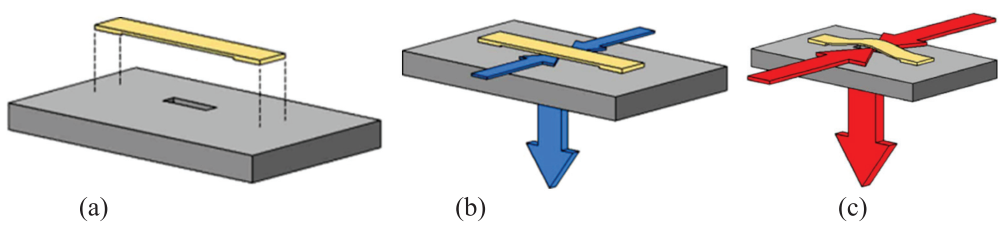

FIGURE 2. Microvalve (a) placement (b) cold position (c) hot position [9]

IMPACT OF THE COOLING DEVICE ON THE CPV PERFORMANCE

To study the impact of this cooling approach, the performance of a CPV receiver composed by 6 strings of 8 PV cells in series [8] is predicted when submitted to an average solar concentration (C) of 600 suns and a non-uniform illumination profile (Figure 3; [7]). Two cooling configurations are compared: cooled by conventional microchannels versus cooled by the proposed matrix of microfluidic cells with individually variable coolant flow rate. The valve aperture has non-linear temperature dependence from its closed shape (until 323 K) up to its fully open shape (at 372 K) ([9]).

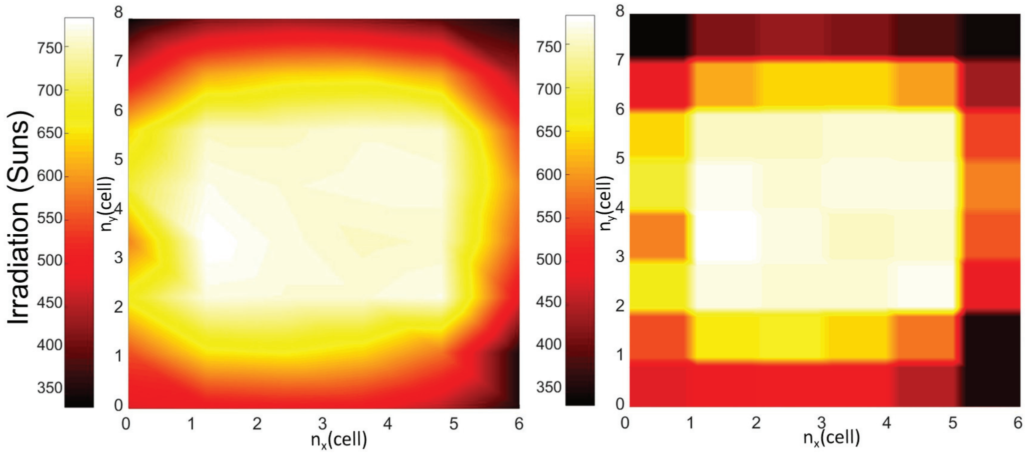

FIGURE 3. (a) Irradiation distribution (b) Irradiation distribution, averaged by PV cell

The characteristics (at 25ºC) of the 1.0 * 1.0 cm^2 PV cells are described in Figure 4 and Table 1 [10].

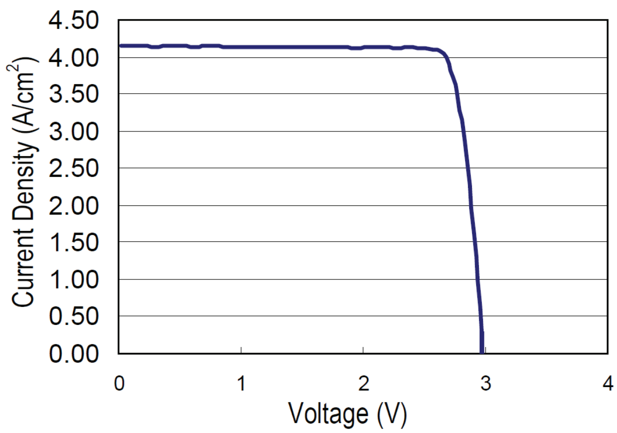

FIGURE 4. Nominal cell IV characteristic curve at 25ºC and 350 Suns [10]

TABLE 1. Typical cell electrical parameters at 25ºC and 350 Suns [10]

Parameter	Value
J_{sc}	4.14 A/cm^2
J_{mp}	4.05 A/cm^2
V_{OC}	2.97 V
V_{mp}	2.64 V
P_{mp}	10.68 W/cm^2
FF	86.9 %
Efficiency	30.5 %

To assess the temperature profile given by the microchannel cooling device an equivalent thermal resistance model is used, with two nodes by PV cell: one relative to the cell temperature and the other to the coolant temperature ([11]). A thermal resistance coefficient of the microchannel device of $5 \cdot 10^{-5}$ Km^2/W [6] is used.

Since convection to the coolant fluid is the dominant heat transfer path and the temperature differences between cells are low (10 K in the whole CPV receiver), lateral conduction between cells is neglected in this study. The non-uniform distribution of the coolant flow rate of the matrix of microfluidic cells is represented in Figure 5. In the case of the proposed cooling device, the thermal behavior of each microfluidic cell is assessed by resolving both the heat transfer obtained by the cooling device (correlation extracted from a CFD numerical model) and the flow rate given by the temperature of the self-adaptive microvalve [9].

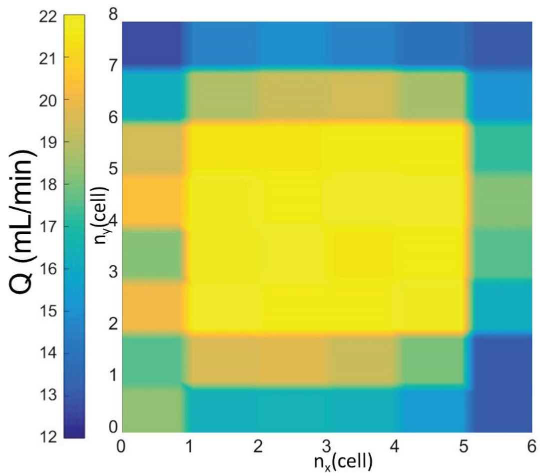

FIGURE 5. Flow distribution for microfluidic cell system

The total flow rates of both cooling devices have been determined in order to reach an identical average temperature (67 ºC) of the CPV receiver and to assess the effect of the temperature non uniformity on the PV output.

The maximum temperature difference of the CPV receiver is 34 K and 10 K for conventional microchannel and the matrix of microfluidic cells, respectively (Figures 6(a) and 6(b)). For the microchannel device, heating of the coolant along the flow path implies a displacement of the maximum temperature with respect to the irradiation pattern. The PV cell characteristic IV curve have been used to calibrate the reduced model used for the assessment of the PV cell power output under different irradiation and temperature conditions. The model can be defined by the following equations (1):

$$I = I_L \frac{C}{C_0} - I_0 \cdot \left[e^{\frac{V}{V_T}} - 1 \right] \tag{1}$$

Where V and I are the potential and the current of the PV cell, respectively. C_0 is the reference solar concentration (350 suns) and I_0 is the cell temperature (T) dependence of the equivalent reverse diode current:

$$I_0 = I_0{}' \cdot T^3 \cdot e^{\left(-\frac{C_1}{K_B T}\right)} \tag{2}$$

Where the $I_0{}'$ is the reverse current factor, independent of the temperature and the thermal voltage V_T, defined as:

$$V_T = \frac{K_B \cdot T \cdot n}{e^-} \tag{3}$$

The obtained values are presented in Table 2:

TABLE 2. Parameters obtained from the reduced model

Description	Symbol	Value
Short-circuit current	I_L	4.14 A
Reverse current factor	$I_0{}'$	0.30419 A/K^3
Equivalent bandgap	C_1	3.1918 J
Ideality reduced factor	n	1.613

The I-V curve of the CPV receiver is assessed and used to determine the maximum power point. The power generated by each cell in these conditions is represented in Figures 6(c) and 6(d). The CPV power generated by the PV receiver cooled by microfluidic cell matrix is 9.6% higher than the one generated by PV receiver cooled by microchannels.

The power generated by each cell in the studied series/parallel configuration is compared to the one that could be produced, in the same illumination and temperature conditions, when the PV cells are electrically isolated. The mismatch losses (Figures 6(e) and 6(f)) are 27.4 and 20.3 % for the microchannel cooling device and the matrix of microfluidic cells, respectively.

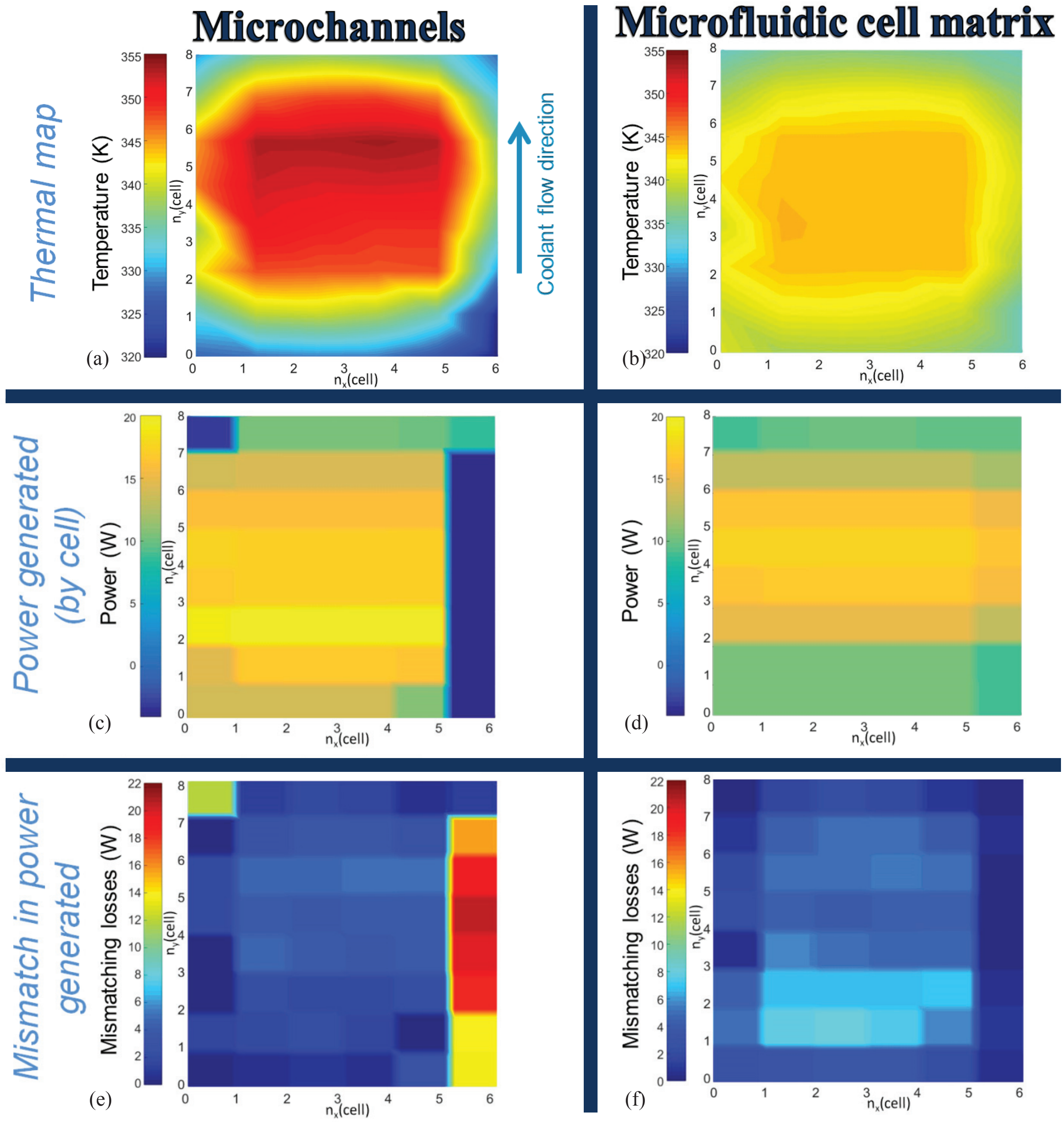

FIGURE 6. a) CPV thermal map cooled by microchannels (average 340.5 K) b) CPV thermal map cooled by microfluidic cell matrix (average 340.5K) c) CPV power generated for each PV cell cooled by microchannels (average 12.5 W) d) CPV power generated for each PV cell cooled by microfluidic cell matrix (average 13.7 W) e) CPV mismatch generated for each PV cell cooled by microchannels (average 4.7 W) f) CPV mismatch generated for each PV cell cooled by microfluidic cell matrix (average 3.6 W).

CONCLUSIONS

The advances in Concentration PV cell technology imply the increase of the Fill Factor and, therefore, lead to higher impacts of the mismatch losses associated to the CPV receiver's temperature non uniformities. The matrix of microfluidic cells with individually variable coolant flow rate is able to provide high temperature uniformities under time dependent and non-uniform heat loads.

Global power generations of the CPV receiver cooled by microchannels and microfluidic cells are, respectively, 72.6% and 79.7% with respect to the sum of the electrically isolated cells production at the same illumination and temperature conditions. At equal average temperature of the CPV receiver power generation using the matrix of microfluidic cells with individually variable coolant flow rate is 9.7% higher than the one with conventional microchannel technology.

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